

Search for flavor lepton number violation in slepton decays at LEP2 and NLC

N.V.Krasnikov *

TH Division, CERN, CH 1211, Geneva 23, Switzerland

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Abstract

We show that in supersymmetric models with explicit flavor lepton number violation due to soft supersymmetry breaking mass terms there must be flavor lepton number violation in slepton decays. We propose to look for flavor lepton number violation in righthanded selectron and smuon decays. For selectron and smuon lighter than 80 GeV flavor lepton number violation in slepton decays could be discovered at LEP2 provided the mixing between selectron and smuon is not small. We also estimate NLC discovery potential of the lepton flavor number violation in slepton decays.

*On leave of absence from INR, Moscow 117312

Supersymmetric electroweak models offer the simplest solution of the gauge hierarchy problem [1]-[4]. In real life supersymmetry has to be broken and the masses of superparticles have to be lighter than $O(1)$ Tev [4]. Supergravity gives natural explanation of the supersymmetry breaking, namely, an account of the supergravity breaking in hidden sector leads to soft supersymmetry breaking in observable sector [4]. For the supersymmetric extension of the Weinberg-Salam model soft supersymmetry breaking terms usually consist of the gaugino mass terms, squark and slepton mass terms with the same mass at Planck scale and trilinear soft scalar terms proportional to the superpotential [4]. For such "standard" supersymmetry breaking terms the lepton flavor number is conserved in supersymmetric extension of Weinberg-Salam model. However, in general, squark and slepton soft supersymmetry breaking mass terms are not diagonal due to many reasons [5]-[15] (an account of stinglike or GUT interactions, nontrivial hidden sector, ..) and flavor lepton number is explicitly broken due to nondiagonal structure of slepton soft supersymmetry breaking mass terms. As a consequence such models predict lepton flavor number violation in μ - and τ -decays [5]-[13]. In our previous note [16] we proposed to look for flavor lepton number violation at LEP2 in righthanded selectron and smuon decays.

In this paper we investigate the "discovery potential" of LEP2 and NLC(next linear collider) of flavor lepton number violation in slepton decays. We find that at LEP2 it would be possible to detect flavor lepton number violation in selectron and smuon decays for slepton masses up to 80 Gev provided that the mixing between selectron and smuon is not small.

In supersymmetric extensions of the Weinberg-Salam model supersymmetry is softly broken at some high energy scale M_{GUT} by generic soft terms

$$\begin{aligned}
- L_{soft} = & m_{3/2}(A_{ij}^u \tilde{u}_R^j \tilde{q}_L^i H_u + A_{ij}^d \tilde{d}_R^j \tilde{q}_L^i H_d + \\
& A_{ij}^l \tilde{e}_R^j \tilde{l}_L^i H_d + h.c.) + (m_q^2)_{ij} \tilde{q}_L^i (\tilde{q}_L^j)^+ + (m_u^2)_{ij} \tilde{u}_R^i \\
& (\tilde{u}_R^j)^+ + (m_d^2)_{ij} \tilde{d}_R^i (\tilde{d}_R^j)^+ + (m_l^2)_{ij} \tilde{l}_L^i (\tilde{l}_L^j)^+ + (m_e^2)_{ij} \tilde{e}_R^i \\
& (\tilde{e}_R^j)^+ + m_1^2 H_u H_u^+ + m_2^2 H_d H_d^+ + \\
& (B m_{3/2}^2 H_u H_d + \frac{1}{2} m_a (\lambda \lambda)_a + h.c.) , \tag{1}
\end{aligned}$$

where i, j, a are summed over 1,2,3 and $\tilde{q}_L, \tilde{u}_R, \tilde{d}_R$ denote the left- (right-)handed squarks, \tilde{l}_L, \tilde{e}_R the left- (right-)handed sleptons and H_u, H_d the two Higgs doublets; m_a are the three gaugino masses of $SU(3)$, $SU(2)$ and $U(1)$ respectively. In most analysis the mass terms are supposed to be diagonal at M_{GUT} scale and gaugino and trilinear mass terms are also assumed universal at M_{GUT} scale. The renormalization group equations for soft parameters [17] allow to connect high energy scale with observable electroweak scale. The standard consequence of such analysis is that righthanded sleptons $\tilde{e}_R, \tilde{\mu}_R$ and $\tilde{\tau}_R$ are the lightest sparticles among squarks and sleptons. In the approximation when we neglect lepton Yukawa coupling constants they are degenerate in masses. An account of the electroweak symmetry breaking gives additional contribution to righthanded slepton square mass equal to the square mass of the corresponding lepton and besides an account of lepton Yukawa coupling constants in the superpotential leads to the additional contribution to righthanded slepton masses

$$\delta M_{sl}^2 = O\left(\frac{h_l^2}{16\pi^2}\right) M_{av}^2 \ln\left(\frac{M_{GUT}}{M_{av}}\right) \quad (2)$$

Here h_l is the lepton Yukawa coupling constant and M_{av} is the average mass of sparticles. These effects lead to the splitting between the righthanded slepton masses of the order of

$$(\delta_{e\mu})_{RR} = \frac{(m_{\tilde{\mu}_R}^2 - m_{\tilde{e}_R}^2)}{m_{\tilde{e}_R}^2} = O(10^{-5}) - O(10^{-3}) , \quad (3)$$

$$(\delta_{e\tau})_{RR} = \frac{(m_{\tilde{\tau}_R}^2 - m_{\tilde{e}_R}^2)}{m_{\tilde{e}_R}^2} = O(10^{-3}) - O(10^{-1}) \quad (4)$$

For nonzero value of trilinear parameter A after electroweak symmetry breaking we have nonzero mixing between righthanded and lefthanded sleptons, however the lefthanded and righthanded sleptons differ in masses (lefthanded sleptons are slightly heavier), so the mixing between righthanded and lefthanded sleptons (for \tilde{e}_R and $\tilde{\mu}_R$) is small and we shall neglect it. In our analysis we assume that the lightest stable particle is gaugino corresponding to $U(1)$ gauge group that is now more or less standard assumption [18]. As it has been discussed in many papers [5] - [15] in general we can expect nonzero nondiagonal soft supersymmetry breaking terms in Lagrangian (1) that leads to additional contributions for flavor changing neutral currents and to flavor lepton number violation.

From the nonobservation of $\mu \rightarrow e + \gamma$ decay ($Br(\mu \rightarrow e + \gamma) \leq 5 \cdot 10^{-11}$ [20]) one can find that [5, 6]-[19]

$$(\delta_{e\mu})_{RR} \leq 10^{-1} M_{av}^2 / (1TeV)^2 \quad (5)$$

For $m_{\tilde{e}_R} = 70GeV$ we find that $(\delta_{e\mu})_{RR} \leq O(10^{-3})$. Analogous bounds resulting from the nonobservation of $\tau \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ decays are not very stringent [5, 6]-[19].

The mass term for righthanded \tilde{e}_R and $\tilde{\mu}_R$ sleptons has the form

$$-\delta L = m_1^2 \tilde{e}_R^+ \tilde{e}_R + m_2^2 \tilde{\mu}_R^+ \tilde{\mu}_R + m_{12}^2 (\tilde{e}_R^+ \tilde{\mu}_R + \tilde{\mu}_R^+ \tilde{e}_R) \quad (6)$$

After the diagonalization of the mass term (6) we find that the eigenstates of the mass term (6) are

$$\tilde{e}'_R = \tilde{e}_R \cos(\phi) + \tilde{\mu}_R \sin(\phi) , \quad (7)$$

$$\tilde{\mu}'_R = \tilde{\mu}_R \cos(\phi) - \tilde{e}_R \sin(\phi) \quad (8)$$

with the masses

$$M_{1,2}^2 = (1/2)[(m_1^2 + m_2^2) \pm ((m_1^2 - m_2^2)^2 + 4(m_{12}^2)^2)^{1/2}] \quad (9)$$

which practically coincide for small values of $m_1^2 - m_2^2$ and m_{12}^2 . Here the mixing angle ϕ is determined by the formula

$$\tan(2\phi) = 2m_{12}^2(m_1^2 - m_2^2)^{-1} \quad (10)$$

The crucial point is that even for small mixing parameter m_{12}^2 due to the smallness of the difference $m_1^2 - m_2^2$ the mixing angle ϕ is in general not small (at present state of art it is impossible to calculate the mixing angle ϕ reliably). For the most probable case when the lightest stable superparticle is superpartner of the $U(1)$ gauge boson plus some small mixing with other gaugino and higgsino, the sleptons $\tilde{\mu}_R$, \tilde{e}_R decay mainly into leptons μ_R and e_R plus $U(1)$ gaugino λ . The corresponding term in the Lagrangian responsible for sleptons decays is

$$L_1 = \frac{g_1}{\sqrt{2}} (\bar{e}_R \lambda_L \tilde{e}_R + \bar{\mu}_R \lambda_L \tilde{\mu}_R + h.c.), \quad (11)$$

where $g_1^2/4\pi \approx 0.13$. For the case when mixing is absent the decay width of the slepton into lepton and LSP is given by the formula

$$\Gamma = \frac{g_1^2}{32\pi} M_{sl} \left(1 - \frac{M_{LSP}^2}{M_{sl}^2}\right)^2, \quad (12)$$

where M_{sl} and M_{LSP} are the masses of slepton and the lightest superparticle (U(1)-gaugino) respectively. For the case of nonzero mixing we find that the Lagrangian (11) in terms of slepton eigenstates reads

$$L_1 = \frac{g_1}{\sqrt{2}} [\bar{e}_R \lambda_L (\tilde{e}'_R \cos(\phi) - \tilde{\mu}'_R \sin(\phi)) + \bar{\mu}_R \lambda_L (\tilde{\mu}'_R \cos(\phi) + \tilde{e}'_R \sin(\phi)) + h.c.] \quad (13)$$

At LEP2 and NLC in the neglect of slepton mixing $\tilde{\mu}_R$ and $\tilde{\tau}_R$ sleptons pair production occurs [21] via annihilation graphs involving the photon and the Z^0 boson and leads to the production of $\tilde{\mu}_R^+ \tilde{\mu}_R^-$ and $\tilde{\tau}_R^+ \tilde{\tau}_R^-$ pairs. For the production of righthanded selectrons in addition to the annihilation graphs we also have contributions from the t-channel exchange of the neutralino [21]. In the absence of mixing the cross sections can be represented in the form

$$\sigma(e^+ e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-) = k A^2, \quad (14)$$

$$\sigma(e^+ e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-) = k (A + B)^2, \quad (15)$$

where A is the amplitude of s-exchange, B is the amplitude of t-exchange and k is the normalization factor. The corresponding expressions for A , B and k are contained in [21]. The amplitude B is determined mainly by the exchange of the lightest gaugino and its account leads to the increase of selectron cross section by factor $k_{in} = (4 - 1.5)$. As it has been mentioned before we assume that righthanded sleptons are the lightest visible superparticles. So sleptons decay with 100 percent probability into leptons and LSP that leads to accoplanar events with missing transverse momentum. The perspectives for the detection of sleptons at LEP2 have been discussed in refs. [21]-[22] in the assumption of flavor lepton number conservation. The main background at LEP2 energy comes from the W -boson decays into charged lepton and neutrino [21]. For $\sqrt{s} = 190$ Gev the cross section of the $W^+ W^-$ production is $\sigma_{tot}(W^+ W^-) \approx 26 pb$. [22]. For selectrons at $\sqrt{s} = 190$ Gev, selecting events with electron pairs with $p_{T,mis} \geq 10$ Gev and the

accoplanarity angle $\theta_{ac} \geq 34^\circ$ [21], the only background effects left are from $WW \rightarrow e\nu e\nu$ and $e\nu\tau\nu$ where $\tau \rightarrow e\nu\nu$. For instance, for $M_{\tilde{e}_R} = 85$ Gev and $M_{LSP} = 30$ Gev one can find that the accepted cross section is $\sigma_{ac} = 0.17pb$ whereas the background cross section is $\sigma_{backgr} = 0.17pb$ that allow to detect righthanded selectrons at the level of 5σ for the luminosity $150pb^{-1}$ and at the level of 11σ for the luminosity $500pb^{-1}$. For the detection of righthanded smuons we have to look for events with two accoplanar muons however the cross section will be (4 - 1.5) smaller than in the selectron case due to absence of t-channel diagram and the imposition of the cuts analogous to the cuts for selectron case allows to detect smuons for masses up to 80 Gev. Again here the main background comes from the W decays into muons and neutrino. The imposition of more elaborated cuts allows to increase LEP2 righthanded smuon discovery potential up to 85 Gev on smuon mass [21, 22].

Consider now the case of nonzero mixing $\sin \phi \neq 0$ between selectrons and smuons. In this case an account of t-exchange diagram leads to the following cross sections for the slepton pair production (compare to the formulae (14,15)):

$$\sigma(e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-) = k(A + B \sin^2(\phi))^2, \quad (16)$$

$$\sigma(e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-) = k(A + B \cos^2(\phi))^2, \quad (17)$$

$$\sigma(e^+e^- \rightarrow \tilde{e}_R^\pm \tilde{\mu}_R^\mp) = kB^2 \cos^2(\phi) \sin^2(\phi) \quad (18)$$

Due to slepton mixing we have also lepton flavor number violation in slepton decays, namely:

$$\Gamma(\tilde{\mu}_R \rightarrow \mu + LSP) = \Gamma \cos^2(\phi), \quad (19)$$

$$\Gamma(\tilde{\mu}_R \rightarrow e + LSP) = \Gamma \sin^2(\phi), \quad (20)$$

$$\Gamma(\tilde{e}_R \rightarrow e + LSP) = \Gamma \cos^2(\phi), \quad (21)$$

$$\Gamma(\tilde{e}_R \rightarrow \mu + LSP) = \Gamma \sin^2(\phi) \quad (22)$$

Taking into account formulae (19-22) we find that

$$\begin{aligned} \sigma(e^+e^- \rightarrow e^+e^- + LSP + LSP) &= k[(A + B \cos^2(\phi))^2 \cos^4(\phi) \\ &+ (A + B \sin^2(\phi))^2 \sin^4(\phi) + B^2 \sin^4(2\phi)/8], \end{aligned} \quad (23)$$

$$\begin{aligned}\sigma(e^+e^- \rightarrow \mu^+\mu^- + LSP + LSP) &= k[(A + B \cos^2(\phi))^2 \sin^4(\phi) \\ &+ (A + B \sin^2(\phi))^2 \cos^4(\phi) + B^2 \sin^4(2\phi)/8],\end{aligned}\quad (24)$$

$$\begin{aligned}\sigma(e^+e^- \rightarrow \mu^\pm + e^\mp + LSP + LSP) &= \frac{k \sin^2(2\phi)}{4} [(A + B \cos^2(\phi))^2 \\ &+ (A + B \sin^2(\phi))^2 + B^2(\cos^4(\phi) + \sin^4(\phi))]\end{aligned}\quad (25)$$

So, as a result of nontrivial slepton mixing, we expect in general the excess of accoplanar $e^+\mu^-$ and $e^-\mu^+$ events compared to the standard background which comes mainly from the leptonic W -decays. Consider at first the case of the maximal mixing $\phi = \frac{\pi}{4}$. For this particular case we find that (here as before we neglect the difference between righthanded selectron and righthanded smuon masses)

$$\begin{aligned}\sigma(e^+e^- \rightarrow e^+e^- + LSP + LSP) &= \sigma(e^+e^- \rightarrow \mu^+\mu^- + LSP + LSP) = \\ \sigma(e^+e^- \rightarrow e^\pm\mu^\mp + LSP + LSP) &= \frac{k(A^2 + (A + B)^2)}{4}\end{aligned}\quad (26)$$

Selecting $e^+\mu^-$ and $e^-\mu^+$ events with $p_{T,mis} \geq 10$ Gev and $\theta_{ac} \geq 34^\circ$ we find in closed analogy with results of ref. [21] that the background cross section which comes mainly from leptonic W -decays for $\sqrt{s} = 190$ Gev is equal to 0.34 pb and the accepted cross section $\sigma(e^+e^- \rightarrow \tilde{l}_R^+\tilde{l}_R^- \rightarrow e^\pm\mu^\mp + \dots)$ is equal to (for $M_{LSP} = 20$ Gev) 0.12pb; 0.09pb; 0.07pb for the slepton masses 75Gev; 80Gev and 83Gev respectively. One can find that for such slepton masses the flavor lepton number violation will be discovered at the level of 9σ ; 7σ ; 5σ for the integrated luminosity $500pb^{-1}$. For nonmaximal mixing we have analyzed two cases:

1. Case A - the neglectation of t-channel neutralino amplitude, selectron cross section coincides with smuon cross section (relatively big LSP mass).
2. Case B - the selectron cross section 3 times bigger than smuon cross section (small LSP mass).

For these two cases we determined 5σ level bound for slepton mixing angle which can be determined at LEP2. The results are presented in table 1. In short, we have found that for slepton masses lighter than 80 Gev LEP2 (if it will be lucky) will discover both sleptons

and flavor lepton number violation (for the case of not small slepton mixing) in slepton decays. For the case of maximal selectron and smuon mixing we expect equal number of e^+e^- , $\mu^+\mu^-$, $e^+\mu^-$ and $e^-\mu^+$ accoplanar events unlike to the standard case (mixing is absent) when there is excess of e^+e^- and $\mu^+\mu^-$ accoplanar events over the accoplanar $e^+\mu^-$ and $e^-\mu^+$ events due to slepton decays with flavor lepton number conservation.

The perspectives for the detection of sleptons at NLC (for the case of zero slepton mixing) have been discussed in ref.[23]. The standard assumption of ref.[23] is that sleptons are the LSP, therefore the only possible decay mode is $\tilde{l} \rightarrow l + LSP$. One possible set of selection criteria is the following:

1. $\theta_{acop} \geq 65^\circ$.
2. $p_{T,mis} \geq 25 \text{ GeV}$.
3. The polar angle of one of the leptons should be larger than 44° , the other 26° .
4. $(m_{ll} - m_Z)^2 \geq 100 \text{ GeV}^2$.
5. $E_{l\pm} \geq 150 \text{ GeV}$.

For $\sqrt{s} = 500 \text{ GeV}$ and for integrated luminosity 20 fb^{-1} , a 5σ signal can be found up to 225 GeV provided the difference between lepton and LSP is greater than 25 GeV [23]. Following ref.[23] we have analyzed the perspective for the detection of nonzero slepton mixing at NLC. In short, we have found that for $M_{LSP} = 100 \text{ GeV}$ it is possible to discover selectron-smuon mixing at the 5σ level for $M_{sl} = 150 \text{ GeV}$ provided that $\sin 2\phi \geq 0.28$. For $M_{sl} = 200 \text{ GeV}$ it is possible to detect mixing for $\sin 2\phi \geq 0.44$ and $M_{sl} = 225 \text{ GeV}$ corresponds to the limiting case of maximal mixing ($\sin 2\phi = 1$) discovery.

It should be noted that we restricted ourselves to the case of smuon selectron mixing and have neglected stau mixing with selectron and smuon. In general case the situation will be slightly more complicated. For instance, for the case of stau-smuon mixing in formulae (23-25) we have to put $B = 0$ (only s-exchange graphs contribute to the cross sections) and in final states we expect as a result of mixing $\tau^\pm \mu^\mp$ accoplanar pairs. The best way to detect τ lepton is through hadronic final states, since $Br(\tau \rightarrow \text{hadrons} + \nu_\tau) = 0.74$. Again, in this case the main background comes from W-decays into $(\tau)^\pm (\mu)^\mp + \nu + \nu$ in the reaction $e^+e^- \rightarrow W^+W^-$. The imposition of some cuts [21, 22] decreases W-

background to $0.07pb$ that allows to detect stau-smuon mixing for slepton masses up to 70 GeV. We have found that for $m_{sl} = 50$ GeV it would be possible to detect mixing angle $\sin(2\phi_{\tau\mu})$ bigger than 0.70. Other detectable consequence of big stau-smuon mixing is the decrease of accoplanar $\mu^+\mu^-$ events compared to the case of zero mixing. For instance, for the case of maximal mixing $\sin(2\phi_{\tau\mu}) = 1$ the suppression factor is 2. In general we can't exclude big mixing between all three righthanded sleptons and as a typical consequence of such mixing we expect the excess of nondiagonal accoplanar lepton pairs.

For the e^+e^- energy less than 160 GeV the WW-background is practically zero [21] so for slepton masses lighter than 70 GeV the best way to detect slepton mixing is the decrease of the energy for LEP2 (LEP1.5).

Let us formulate the main result of this paper: in supersymmetric extension of standard Weinberg-Salam model there could be soft supersymmetry breaking terms responsible for flavor lepton number violation and slepton mixing. If sleptons are relatively light and mixing is not small it would be possible to discover both sleptons and lepton flavor number violation in slepton decays at LEP2.

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Table 1. LEP2 5σ discovery potential for selectron-smuon mixing angle $\sin 2\phi$ for different slepton masses and for $L = 500pb^{-1}$

M_{sl} in Gev	$\sin 2\phi$	$\sin 2\phi$
	case A	case B
50	0.60	0.40
55	0.64	0.44
60	0.69	0.46
65	0.75	0.50
70	0.85	0.57
75	0.96	0.67
80	-	1

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